High Wind Upper Ocean Mixing with Explicit Surface Wave Processes

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Grant Number: N00014-09-C-0088

LONG-TERM GOALS

The work described here supports the Office of Naval Research Departmental Research Initiative (DRI) for research on the "Impact of Typhoons on the Western Pacific Ocean" (ITOP). The theme of the DRI is to better characterize and predict the ocean boundary layer (OBL) and its impact on typhoon (hurricane) evolution. This is one component of developing improved prediction models for the coupled atmosphere-ocean-wave system. Cooling of the sea surface temperature (SST) is a critical coupling variable influencing atmosphere-ocean hurricane dynamics; SST is largely determined by OBL turbulence, surface wave processes, and mixed layer entrainment. Our research goal is to model the strongly forced wind and wave driven upper OBL using turbulence resolving large-eddy simulation (LES) with explicit wave effects, *viz.,* wave-current interactions and breaking waves and examine their impact on ocean mixing during hurricane events.

OBJECTIVES

The specific research objectives for ITOP are: (1) conduct process studies using LES of the OBL with different combinations of time varying large scale forcings and surface wave effects and examining their impact on ocean mixing; (2) evaluate and compare these LES results with predictions obtained using a 1-D column model of the OBL based on the K-Profile Parameterization (KPP); and (3) compare our simulation results with available observations. Inertial resonance, storm residence time, and the larger scale environment are some of the processes to be examined in our simulations.

Report Documentation Page					*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE **2010**		2. REPORT TYPE			3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **High Wind Upper Ocean Mixing with Explicit Surface Wave Processes**					5a. CONTRACT NUMBER
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)					5d. PROJECT NUMBER
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Center for Atmospheric Research,Boulder,CO,80307-3000**					8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S)
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

In order to examine the dynamics of the upper ocean boundary layer under high wind forcing we developed an LES model of the OBL that accounts for surface wave effects through non-conservative breaking waves and phase-averaged, conservative wave-current interactions which lead to Langmuir circulations (Sullivan *et al.* 2007). The equations for the resolved flow components are the Craik-Leibovich (CL) theory with crucial wave-current coupling through the vortex force. The larger scale forcing (momentum and scalar fluxes) and wave fields are externally imposed in the LES.

WORK COMPLETED

Meetings: We attended a PI meeting in Taichung Taiwan that focused on refining elements of the ITOP field campaign. The discussion concentrated on the deployment of the numerous drifters, buoys, and floats and the coordination with the aircraft.

OBL LES: We concentrated on adapting our large-eddy simulation code for the OBL to a high wind regime with time varying winds, surface scalar fluxes, and wave fields. For our LES process studies, Hurricane Frances is selected as a canonical storm (*e.g.,* see Sanford *et al.* 2007). Hurricane Frances had a radius of maximum winds $R = 40$ km with a surface rotational wind speed $V_r \sim 50\text{ms}^{-1}$ (see Zedler, 2007).

The general design of the LES experiments is to pass a hurricane vortex over small LES domains as sketched in figure 1. Then the surface fluxes and wave fields imposed at the water surface vary with time depending on the storm propagation speed V_s and the location of the LES domain (x_{LES}, y_{LES}) within the storm track (see discussion in RESULTS). Our process studies examine the impact of resonant and anti-resonant wind and inertial-current forcing by locating LES domains to the right and left of the storm track.

The initial temperature state of the OBL for all the LES experiments is neutrally stratified over the region -33 m $< z < 0$ m bounded by a stable inversion of 0.05 C m^{-1} for $z < -33$ m. The LES domain $(X_L, Y_L, Z_L) = (750, 750, -195)$m is discretized using $(N_x, N_y, N_z) = (500, 500, 160)$ gridpoints; the vertical spacing varies smoothly from $\triangle z = 1.0$ m near the water surface to about $\triangle z = 1.4$ m near the lower boundary. Each simulation is first run from a cold start for a period of $\sim$ 10 hours to generate turbulence. The LES is then restarted using these archived turbulent flow fields as initial conditions. For LES experiments with wave effects, we set the turbulent Langmuir number $La_t = (0.3, 0.5, \infty)$ and wave age $= 0.6$ which fixes the parameters in an exponential Stokes drift profile (Sullivan & McWilliams, 2010). More than 190,000 timesteps are needed to cover the entire 60 physical hours of interest for cases located along the path of maximum wind speed. We note that the OBL LES code used here is a variant of the new highly parallel atmospheric code that is being developed for the high resolution air-sea interaction (HIRES) DRI[1]. The algorithm is based on an incompressible Boussinesq flow model and solves the governing equations utilizing a mixed finite-difference pseudospectral scheme.

[1] For a description of Hi-Res see http://airsea.ucsd.edu/hires/.

The parallelization is accomplished utilizing the Message Passing Interface and a 2-D domain decomposition, see Sullivan & Patton (2008) for further details.

RESULTS

A typical time history of wind and thermal forcing applied at the top of the simulations is given in figure 2 for an LES domain located 55 km to the east and 700 km north of the storm center depicted in figure 1. In this simulation, the hurricane vortex propagates northward with a speed of 5.5 $\mathrm{m\,s^{-1}}$ and thus the maximum winds occur at 35.4 hours into the simulation; the maximum wind speed is about 43.5 $\mathrm{m\,s^{-1}}$. At this location, *i.e.,* to the right of the storm track, the winds and wind stress rotate clockwise with a time scale approaching an inertial period $T = 2\pi/f$. Inspection of figure 2 indicates that over the time period 0 to 10 hours, the winds are modest $\mathcal{O}(5\ \mathrm{m\,s^{-1}})$ while the surface heat fluxes are $\mathcal{O}(100\ \mathrm{W\,m^{-2}})$. Also the wave forcing is small because of small values of Stokes drift. Hence shear, convection, and wave-current interactions all play a role in forcing the OBL. Beyond 10 hours, shear forcing and wave-current interactions dominate because of the rapid increase in the surface winds.

The presence and impact of Langmuir cells in our solutions is identified using flow visualization and quantified using statistical measures. Vertical velocity w' is one of the most robust and clear indicators of Langmuir circulations in simulations with wave-current interaction (*e.g.,* see McWilliams, *et al.* 1997). Measurements of vertical velocity, obtained from near neutrally buoyant Lagrangian floats (Tseng & D'Asaro, 2004), can also be used to detect the presence of Langmuir circulations. Figure 3 shows contours of normalized vertical velocity w'/u_* in $x-y$ planes near the water surface $z \sim -5$ m at different simulation times; the selected times bracket the time of maximum winds. Each panel also shows a wind vector oriented in the mean wind direction. Inspection of the images shows coherent structures elongated along the axis of the mean wind direction which we identify as Langmuir cells. The overall impression is that these coherent structures are geometrically similar to their counterparts found at much lower wind speeds, *e.g.,* see McWilliams *et al.* (1997). In the present solutions the cells rotate with the time varying wind direction but still display mergers and junctions as in simulations with steady forcing. Notice also that at the time of maximum winds $t \sim 35$ hours, the Langmuir cells remain coherent and are readily identified in the images.

The impact of Langmuir cells in the high wind OBL is also apparent in turbulence statistics. Figure 4 compares time histories of vertical velocity statistics from three different LES with varying vortex force, *viz.,* $La_t = (\infty, 0.5, 0.3)$. Note $La_t = \infty$ is a simulation with no vortex force while $La_t = 0.3$ is a simulation with the strongest wave-current interaction. In order to construct these statistics, we first compute the vertical profiles $\langle w^2 \rangle(z,t)$ and $\langle w^3 \rangle(z,t)$ at each time step of the LES; here $\langle\ \rangle$ denotes a horizontal spatial average over an $x-y$ plane. We then sweep through these profiles to locate the maximum in the second-order moment $\langle w^2 \rangle_{max}$ and minimum in the third-order moment $\langle w^3 \rangle_{min}$. The temporal variation of these two statistics are given in figure 4. Langmuir cells, generated by vortex forces, impact the vertical velocity and the overall turbulence level and mixing in the OBL for time greater than 10 hours. Even with relatively weak wave-current interactions, *viz.,* $La_t = 0.5$, the second and third order moments differ from the simulation with no vortex force. Grant & Belcher (2009) propose $w_L = u_*/La_t^{2/3}$

as the velocity scale characteristic of the Langmuir turbulence regime. For the present computations we hold the turbulent Langmuir number fixed but friction velocity u_* varies considerably and thus the simulations sweep through a wide range of w_L. Our values of $\langle w^2 \rangle_{max}$ and $\langle w^3 \rangle_{min}$, obtained with time varying forcing, are broadly consistent to those obtained by Grant & Belcher (2009) during the time period 15 hours $< t <$ 40 hours. One of the future tasks is to examine if the velocity scale w_L collapses vertical profiles of important OBL turbulence statistics for these high wind simulations.

The third-order moment $\langle w^3 \rangle$ is one component of the vertical transport term $T = -\partial \langle wq^2 \rangle / \partial z$ which appears in a classical turbulence kinetic energy budget (q^2 is the total turbulence kinetic energy). In figure 5 we show vertical profiles of $T_w = -\partial \langle ww^2 \rangle / \partial z$ normalized by friction velocity and boundary layer depth h. In the LES with no wave effects this transport term is small with little vertical structure as expected for a shear driven boundary-layer flow. The inclusion of wave-current interaction in the simulations generates coherent Langmuir cells that alter the turbulent transport in striking ways (see Grant & Belcher, 2009). Significant transport of vertical variance from the surface layer to regions deeper in the OBL is induced by the Langmuir cells. This enhances the overall mixing in the OBL. For example, LES solutions show that the OBL deepens and the SST is cooled in the presence of wave effects (not shown). However, we find that most of the change in these two statistics, caused by wave effects, occurs in the time period before the time of maximum winds.

IMPACT/APPLICATIONS

The LES results obtained here for hurricane driven OBLs can be used to guide the interpretation of observations collected during the ITOP program. In addition, the results can be used to test simpler 1-D parameterizations of the ocean mixed layer that are used in large scale models. Our particular interest is in evaluating and improving the so-called K-profile parameterization (KPP) that is routinely used in the Regional Ocean Modeling System (ROMS).

TRANSITIONS & RELATED PROJECTS

The present work has links to the ONR DRI on High Resolution Air-Sea Interaction (HIRES) that focuses on the interaction of waves and turbulence in the atmospheric surface layer. The LES model being developed for HIRES is also being used in the present work.

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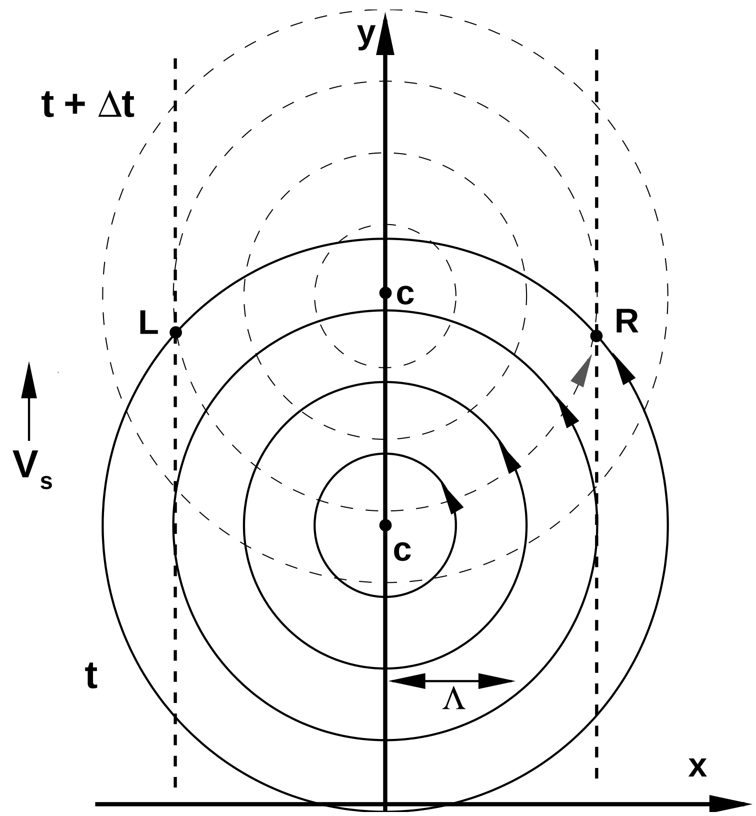

Figure 1: Sketch of an idealized hurricane vortex used for setting the surface conditions in LES. The vortex is propagating upward with speed V_s and has a characteristic length scale (radius of maximum winds) Λ. The families of solid and dotted circles indicate the position of the vortex at initial time t and at a later time $t + \triangle t$, respectively. The fixed LES domains to the right (R) and left (L) of the vortex center (c) feel the time history of wind speed and direction along the dotted vertical lines.

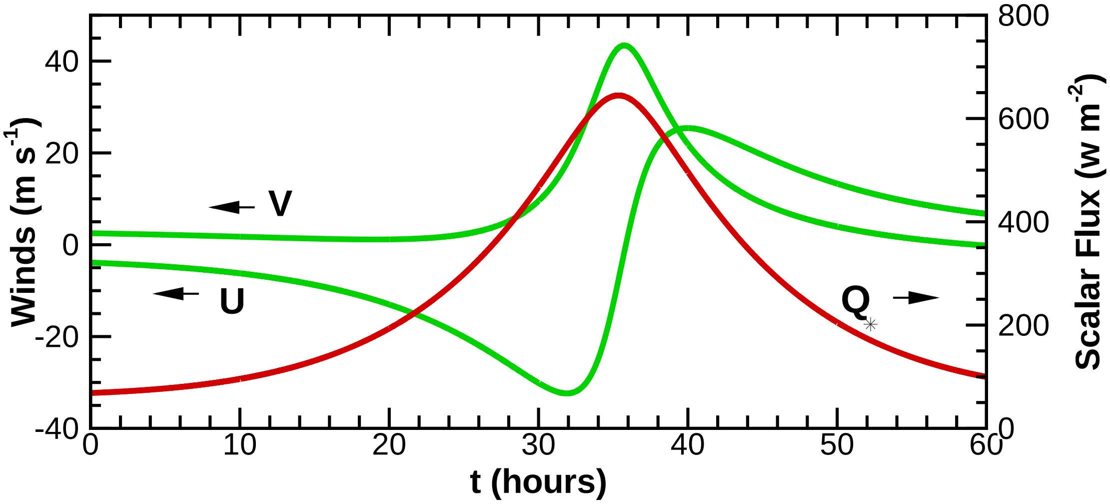

Figure 2: *Temporal variation of the wind and thermal forcing applied at the top of the ocean boundary layer. The LES domain in figure 1 is located 55 km to the east and approximately 700 km north of the hurricane vortex center. The vortex propagates vertically at 5.5 m* s^{-1}.

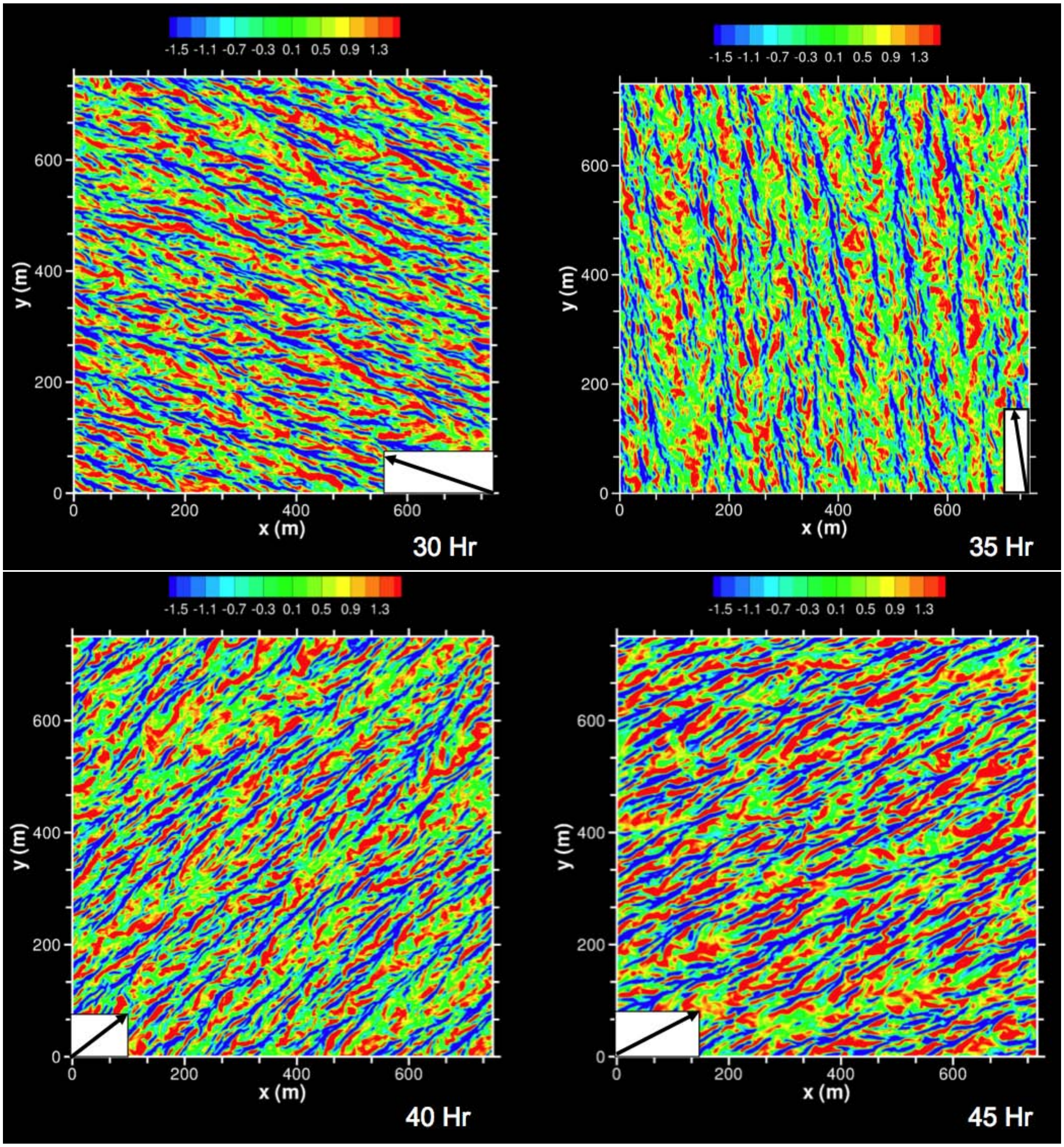

Figure 3: *Contours of vertical velocity normalized by friction velocity u_* near the water surface at different times in the LES simulation of a hurricane driven ocean boundary layer. The elongated downwelling lines (blue contours) mark the boundaries between neighboring Langmuir cells. Forward looking Y-junctions indicate mergers between neighboring cells. The black vectors show the direction of the surface wind applied at the top of the water surface. Notice how the direction of Langmuir cells mirrors the changing rotation of the wind. In these simulations the turbulent Langmuir number $La_t = 0.3$.*

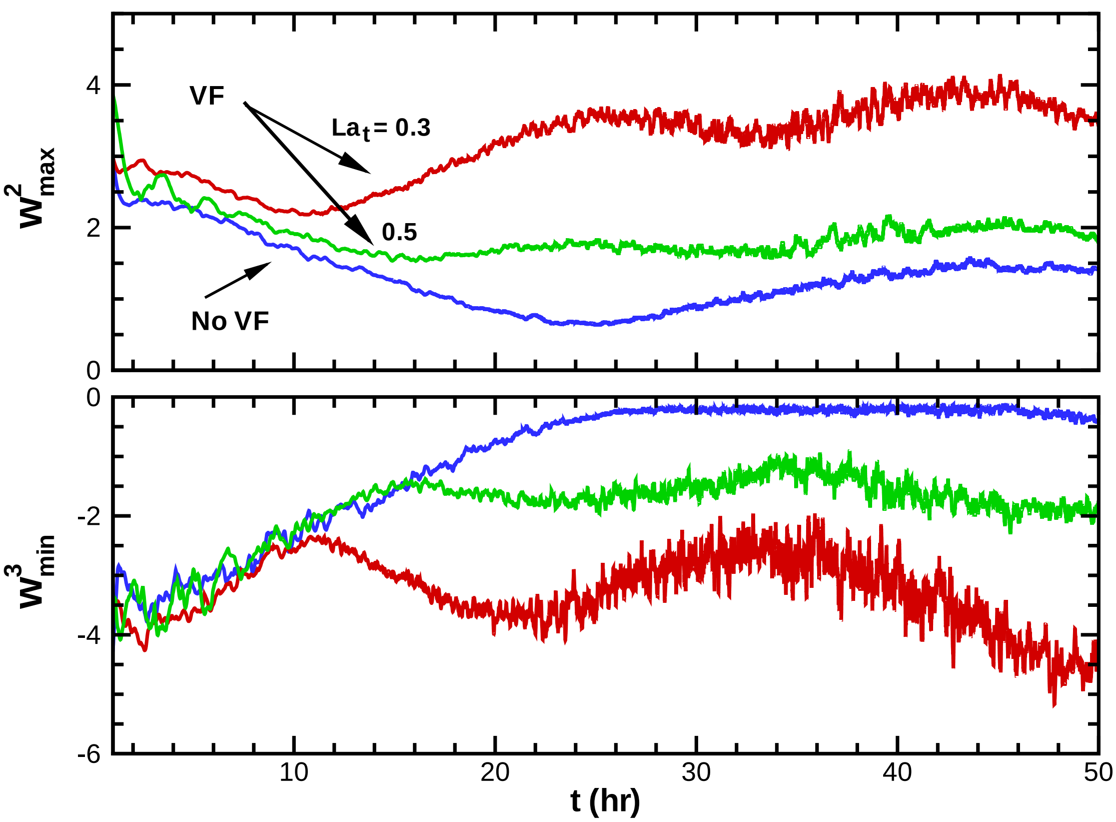

Figure 4: *Variation of the maximum vertical velocity variance (upper panel) and minimum third-order moment (lower panel) for simulations at different turbulent Langmuir numbers* La_t=$(\infty, 0.5, 0.3)$ *(blue, green, red) curves respectively. The time of maximum winds occurs at about* $t = 36$ *hours into the simulation. The variance and third-order moment are normalized by* u_*^2 *and* u_*^3*, respectively.*

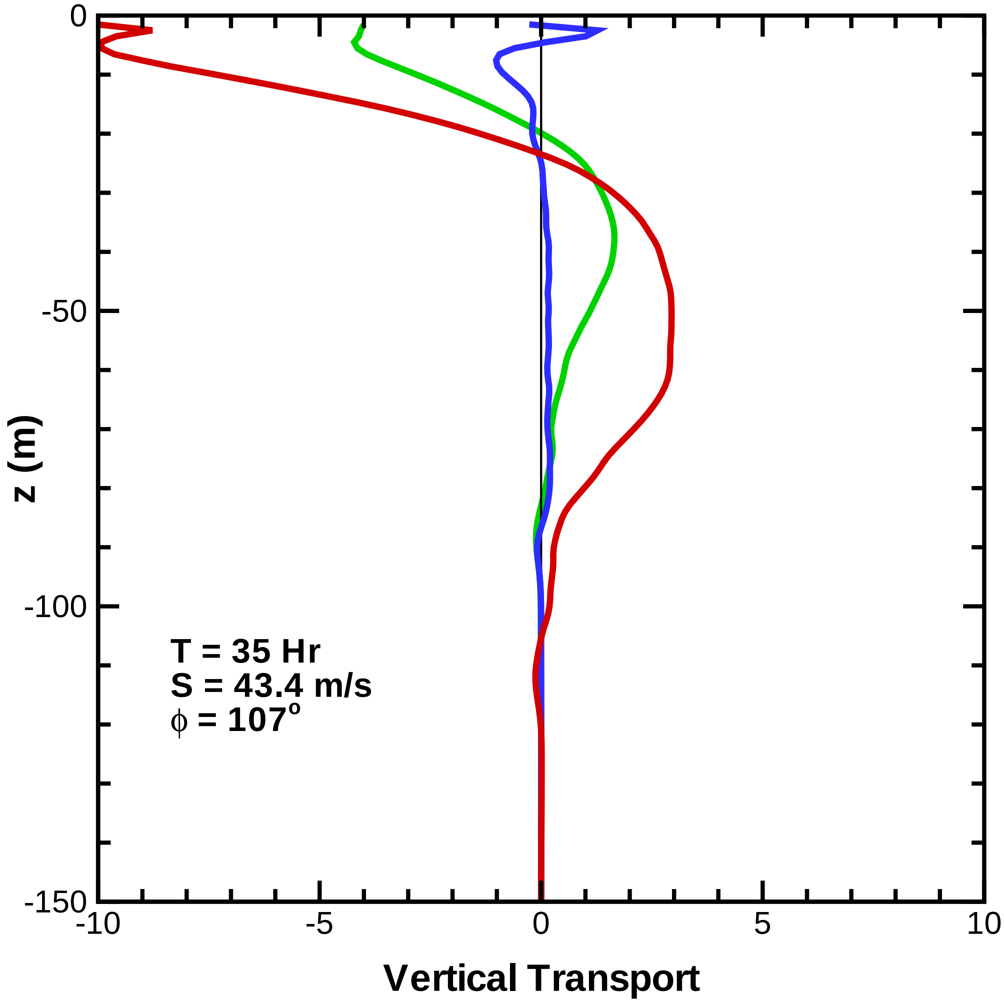

Figure 5: *Vertical profile of the (resolved) vertical transport term* $T = -\partial\langle ww^2\rangle/\partial z$ *which appears in the turbulent kinetic energy (TKE) equation. The vertical transport is normalized using the ocean boundary layer depth* h *and friction velocity* u_**. The results are obtained at* t*=35 hours when the surface wind speed* $S \sim$ *43.4 m* s^{-1}*. The winds are aligned at 107 degrees from the horizontal. The turbulent Langmuir number* $La_t = (\infty, 0.5, 0.3)$ *(blue, green, red) curves respectively. Notice in the case with strong wave effects (red curve) turbulent kinetic energy is transported from the surface layer to deeper depths in the boundary layer which enhances the entrainment of cool water.*